

CONSTRAINTS ON TRANSPORT AND EMPLACEMENT MECHANISMS OF LABILE FRACTIONS IN LUNAR COLD TRAPS. D. Rickman¹ and L. Gertsch², ¹NASA (Earth Science Office/MSFC/NASA, 320 Sparkman Drive, Huntsville, AL 35805, doug.rickman@nasa.gov), ²Missouri University of Science and Technology (Rock Mechanics & Explosives Research Center, 1006 Kingshighway, Rolla, MO 65401, GertschL@mst.edu).

Introduction: Sustaining the scientific exploration of the Solar System will require a significant proportion of the necessary fuels and propellants, as well as other bulk commodities, to be produced from local raw materials [1]. The viability of mineral production depends on the ability to locate and characterize mineable deposits of the necessary feedstocks. This requires, among other things, a workable understanding of the mechanisms by which such deposits form, which is the subject of Economic Geology.

Background: Current understanding of the distribution, abundance, and mechanisms of transport and emplacement of lunar volatiles are very problematic [2], a point brought out by most authors discussing lunar volatiles [3] [4]. There are many speculative models about transport mechanisms and sources [5] [6] though residence times are unknown [7]. Although available data are either very limited (LCROSS, GRAIL) or ambiguous (LAMP, radar, LEND, M3), some constraints on the transport and deposition mechanisms at work can be deduced.

First, it is important to understand what is being considered. The term “volatile” refers to easily mobilized materials that “leave the scene”. LCROSS data, however, show that some do not leave. “Labile” is a more accurate term; it means something that moves. This paper further considers only ions, atoms, or molecules, in contrast to solid phases.

The list of known lunar labiles is intriguing: H₂O; Hg; ultra-light species (H₂S, NH₃, SO₂, C₂H₄, CO₂, CH₃OH, CH₄, OH, CO) [2]; Br [8]; Ar [5] (a true volatile); and soluble and insoluble organic matter (IOM). The latter two, though not identified, must be included as they are now known as substantial components of comets [9]. Only traces of C are found in Apollo samples [10]. Given the molecules of (3), additional molecules known in comets should be anticipated as well [11]. The LCROSS and LAMP observations of Hg [12] suggest the possible presence of elements such as Ag, Se, Te, etc.

Direct observation of significant concentrations has been limited to LCROSS and GRAIL data. The LCROSS impact was in Cabeus Crater, 100 km wide, at latitude 81.5° S. The GRAIL impacts were farther from a pole (75.6° N) and on the slope of a massif. There LAMP detected H and Hg, but study of these results is not as advanced as for LCROSS so they are not used substantially here.

For this discussion we assume that concentrations of labile molecules on the Moon are geographically limited to polar-region cold traps.

General Constraints: Several constraints on the transport and/or concentration mechanisms in lunar cold trap environments should be studied.

Species Applicability. First, the mechanisms must, singularly or together, work for all labiles detected. Further, they should be able to explain observed relative abundances. Until better data arise, e.g. from on-site sampling, we assume that all species listed above are present in the lunar cold traps.

Relative Ages. Cabeus Crater formed after the lunar crust stabilized. The LCROSS-observed labiles are younger than the host regolith, which is younger than the crater, though the particles composing it are older.

Detection Constraints. Neutron detectors are sensitive to H. Radar is interpreted as sensitive to water ice, but for neither are controls well-constrained. These instruments are blind to other labile molecules, due to the fundamental concepts employed in their operation. Also, the spatial resolution of the observations varies between instruments and missions.

Ore Sources: The original source for the observed labiles must be within, beneath, or outside their current location, which for LCROSS is a crater.

If the source is inside the crater and the labiles can move without leaving it, gravity would concentrate them at lower elevations (all else equal). However, the detection of Hg from GRAIL impacts on the side of a massif suggests that gravity concentration is not dominant. The observations of [13], while relevant for H₂O, do not explain the presence of other molecules observed by LCROSS. [14] suggests a possible source for some but does not match the observations.

Within the Crater. Deposits of volatile materials on the lunar surface from whatever source would rapidly sublime into space, an unlikely main origin.

Beneath the Crater. If the labiles came from crustal rock, multiple processes are required to create and move them through the crust to the shallow regolith depths where LCROSS impacted them.

The terrestrial equivalents of the mafic and ultramafic magmas postulated for the Moon are “dry” compared to those associated with granitic intrusions, so it seems likely that lunar magmas likewise would not be significant sources.

Furthermore, movement of magmatic water on Earth leaves obvious petrologic signs, which are absent in Apollo samples and lunar meteorites.

The combination of labiles reported from LCROSS does not match that expected from terrestrial layered mafic intrusives [15]. These lines of evidence indicate that the source of the labile molecules in Cabeus is not beneath the crater floor.

Nearby on the Surface. If the labile fractions originated in the near-surface outside the crater, they must have moved through crustal rock, through regolith, across the lunar surface, and/or through space.

Cabeus is an eroded crater with subdued walls. Light molecules outside the crater could move through fractures or the regolith blanket, but crater wall exposure to these reservoirs would be limited.

Hypervelocity impact pressure waves can transmit enough energy to break down impacted rock into constituent ions. A deposit of labiles could form where the transient conditions return to pressures and temperatures at which they re-condense. This would form a spherical shell around the impact point, within the pores of the near-field rock and regolith.

Each mechanism above could contribute to these sites, but they do not satisfy the implied masses.

Directly from Space. Much of the labile material probably arrived directly from space, either as a limited number of large masses, such as comet nuclei or ejecta blocks, or as diffuse molecules [16].

Major constraints on the two end members are: (1) The weak reflectivity in radar and visible light and the nature of the neutron flux preclude large areas covered by water ice. (2) Epithermal neutron data clearly show pole-ward enhancement at scales of 10-100 km [17]. (3) LAMP data suggest widespread water frost [18]. (4) M3 shows polar-ward increases in OH concentration [13]. (5) LEND epithermal neutron concentrations correlate with slope aspect [19].

Source Types: If the labile molecules come from space, in what form do they arrive?

Point Sources: Compared to the large “footprints” of other missions, LCROSS data are from a point. However, direct creation of deposits by single impacts is difficult to accept as a major cause of the observed concentrations, given the broad, extensive features observed by widely different techniques [17].

No known point source has the Hg content seen by LCROSS. A separate source may be responsible for the Hg, and perhaps for other molecules [20].

Diffuse Sources. Study is underway of several likely mechanisms by which labiles can enter the regolith from space, into either the solid grains (perhaps restricted to certain types) or the pore spaces. This includes the solar wind, its interactions with the lunar

atmosphere, and surface transport of species from the point sources discussed above [16] [21].

Molecules deposited from vacuum at low temperature may form amorphous rather than crystalline solids. The presence of other molecules may either inhibit or seed crystallization. The material may be amorphous at near atomic scales or it may qualify technically as glass. Alternatively, unexpected compounds could form (e.g., terrestrial deposits of methane clathrate were found only recently, but are abundant in certain regions).

The rates of deposition from diffuse sources would be very slow compared to deposition by water-related mechanisms on Earth. This greatly limits the possible textures of regolith and labile materials, which in turn affects the mineability (from both the excavation and processing perspectives) of potential ores.

Conclusions: Multiple deposition scenarios are possible for labile materials on the Moon. This paper suggests labile fractions moved diffusely through space; deposits may grow richer with depth until low porosity rock; lateral transport is likely to have occurred with the regolith, at least for short distances; crystalline ice may not exist; the constituent phases could be extremely complex. At present we can constrain the sources only mildly; once on the Moon, the transport mechanisms inherently mix and therefore obscure the origins. However, the importance of expanding our understanding of ore-forming processes on the Moon behooves us to make the attempt. Thus begins a time of new inquiry for Economic Geology.

References: [1] Sanders G. *et al* (2005) 7th ILEWG Conf, Toronto. [2] Colaprete A. *et al* (2010) *Science* 330, 463-468. [3] Hurley D.M. *et al* (2012) *Geoph Res Ltr* 39/9, 6p. [4] Gladstone *et al.* (2012) *JGR* 117, 13p. [5] Hodges R.R. (1981) *LPSC XII*, 451-453. [6] Schorghofer N. (2012) *LPSC XLIII*, #1659. [7] Siegler M.A. *et al* (2011) *JGR* 116, 18p. [8] Jovanovic S. and Reed G.W. (1979) *LPSC X*. [9] Levasseur-Regourd A.C. and Lasue J. (2011) *Meteoroids: The Smallest Solar System Bodies*, 66-75. [10] Steele A. *et al* (2010) *Science* 329, 51. [11] Greenberg J.M. (1998) *Astron Astroph* 380/30, 375-380. [12] Retherford K.D. *et al* (2013) 45th AAS DPS. [13] McCord T.B. *et al* (2011) *JGR* 116. [14] Berezhnoy A.A. (2013) *Icarus* 226, 205-211. [15] Ashwal L.D. (1993) *Anorthosites*, Springer-Verlag. [16] Crider D.H. and Vondrak R.R. (2000) *JGR* 105, 26773-26782. [17] Litvak M.L. *et al* (2012) *JGR* 117, 18p. [18] Gladstone G. *et al* (2010) *Science* 330, 472-476. [19] McClanahan T.P. *et al* (2013) *LSI Virtual Forum*. [20] Dikov Yu.P. *et al.* (2002) *Sol Sys Res* 36, 1-11. [21] Barghouty A.F. *et al.* (2011) *Nuc Instr Methods in Physics Res Sec B*, 1310-1315.